OBJECTIVE FORECASTS OF DAILY AND MEAN SURFACE TEMPERATURE[1]

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[Manuscript received August 8, 1961; revised October 4, 1961]

ABSTRACT

Multiple regression equations for predicting 5-day mean temperatures in the United States were originally computed from 5-day mean values of both 700-mb. height and surface temperature, but they gave better results operationally when applied to properly weighted 36-hour forecasts of height and temperature. Since re-derivation from daily instead of mean data yielded poorer results, it appears that use of prognostic daily values as input in equations computed from mean data produces the best mean forecast under current operating conditions.

In an effort to obtain daily temperature forecasts for several days in advance, 5-day mean objective temperature predictions were tested as forecasts of daily mean temperature on each of the individual days comprising the forecast period. Although perfect mean forecasts would have been most accurate for the middle day of the period, the objective prognoses attained maximum accuracy a day or two earlier. Comparison is made with chance, persistence, climatology, and daily predictions prepared at local forecast offices. The objective forecasts were superior to these controls on each day of the 5-day period, with maximum difference on day 3. Additional tests of the skill of the objective predictions as 2- and 3-day forecasts are described, and it is concluded that the objective method can be of assistance in the routine preparation of 72-hour forecasts.

1. INTRODUCTION

In previous papers by the authors [6, 7], an objective method for forecasting 5-day mean temperatures over the United States was derived. In the present paper, after a brief review of this method (section 2) and the time periods involved (section 3), the results of applying several modifications on an operational basis will be presented in section 4. An investigation of the accuracy of the objective method and various controls during each day of the 5-day period will then be described in section 5. Finally, some attempts to use the method for preparing daily temperature forecasts for 2 and 3 days in advance will be discussed (section 6).

2. EXAMPLE OF THE OBJECTIVE METHOD

The objective method was originally derived using an electronic computer by applying a stepwise method of multiple regression, known as the screening procedure [9], to 10 years of observed 5-day mean 700-mb. heights and surface temperatures.[2] Typical results are presented in figure 1 for Cleveland, Ohio during the winter season. The most important single predictor of Cleveland's mean temperature during the next 5 days is the 5-day mean temperature centered on forecast day at Indianapolis, Ind., and the correlation between the two variables is 0.60. The positive sign of the regression coefficient preceding Indianapolis in the prediction equation written at the top of the figure indicates that low temperatures in that city tend to be followed by cold weather in Cleveland, and conversely for warm conditions.[3]

The second most important predictor is the 5-day mean 700-mb. height centered 2 days after forecast day in northwestern Canada at 60° N., 120° W. The combination of height at this point plus temperature at Indianapolis yields a multiple correlation of 0.71. The coefficient of this variable has a negative sign, as expected from the fact that high heights in a ridge of large amplitude in northwestern Canada produce strong northwesterly flow of cold polar air and hence low temperatures at Cleveland, while low heights lead to mild Pacific air in strong westerly flow [8].

Combination of the first two predictors with an additional one produces best results when the 700-mb. height at 40° N., 90° W. is used, raising the multiple correlation to 0.76. The positive sign of the coefficient before this variable suggests that high heights at this point lead to warm temperatures at Cleveland, while low heights are followed by cold weather.

The fourth predictor is the current temperature at Bismarck, N. Dak. which raises the multiple correlation to 0.78. The positive sign of its coefficient, like that of the temperature at Indianapolis, reflects the prevailing west to east drift of air masses. Similar results were

[1] Based upon paper presented at joint meeting of American Meteorological Society and American Geophysical Union, Washington, D.C., April 19, 1961.

[2] References to heights and temperatures throughout this paper should be understood to apply to their anomalies, or departures from local normal, rather than to their absolute values.

[3] Strictly speaking, the coefficients in the multiple regression equation should not be interpreted as simply as has been done in this section since they reflect the joint, rather than the individual, contribution of the various predictors. However, inspection of numerous temperature prediction equations containing from 1 to 8 variables indicates that, at least for this type of data, the regression coefficients may fluctuate in magnitude as additional terms are added. but they rarely change in sign.

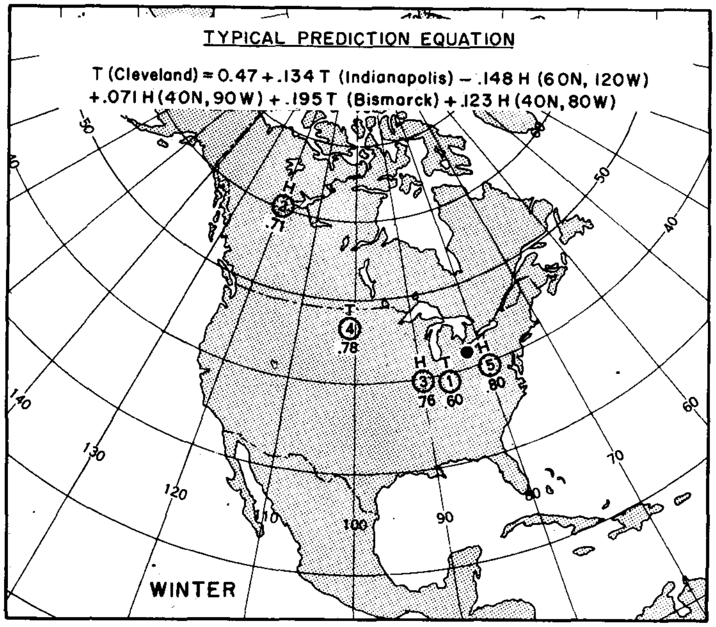

FIGURE 1.—Multiple regression equation used in predicting 5-day mean temperature at Cleveland, Ohio (located by heavy solid dot) during the winter season, as a function of 5-day mean 700-mb. height centered 2 days later (H) and 5-day mean surface temperature centered on forecast day (T) at points given in parentheses. The location of the predictors is given by the open circles, the order of selection by the number inside the circle, the type of variable by the letter above the circle, and the multiple correlation coefficient after inclusion of the given predictor by the decimal below the circle.

obtained by Wadsworth [13] in a statistical study of daily temperatures at Columbus, Ohio.

The fifth predictor is the 700-mb. height in the vicinity of Cleveland at 40° N., 80° W. Its positive coefficient, like that of the height selected earlier at 40° N., 90° W., reflects the fact that ridges are usually warm and troughs cold (See [10] for a discussion of this phenomenon.) At this point the screening process was stopped because no additional predictor produced any significant increase in the multiple correlation of 0.80 attained by these five variables.

Similar equations have been derived for each season of the year for 39 cities covering most of the United States. In all cases the equations appear to be physically reasonable. Consequently, they are quite stable; i.e., they gave nearly as good results in tests on independent samples as they did on the original developmental data [7]. However, these tests were made using *observed* 5-day mean values of all predictors; in actual forecast practice, *prognostic* values must be used in the equations, and the results obtained are quite different.

3. SCHEMATIC CALENDAR

In order to amplify the last point, a schematic calendar has been prepared as shown in figure 2. Let us call day 0 the day on which the forecasts are made in the Extended Forecast Branch. The 5-day mean forecasts apply to the period centered 4 days after forecast day and therefore designated T_4. The 5-day mean 700-mb. heights used in deriving the objective method were taken from an earlier period, centered 2 days after forecast day and designated H_2, while the temperature predictor was taken still earlier, centered on forecast day, and designated T_0. Thus, as originally derived, the objective method gave T_4 as a function of T_0 and H_2.

In the actual forecast routine, the values of T_0 and H_2 had to be estimated. Half of the values that contribute to T_0 had already been observed, and the other half was estimated from forecasts routinely prepared for shippers each morning at local Weather Bureau forecast offices throughout the country and commonly called FM's [12]. H_2 was taken as the mean of the daily heights, observed on day 0 and forecast for each of the next 4 days by the barotropic model at the National Meteorological Center (NMC) at Suitland, Md. [2, 3].

However, after considerable experimentation, it was found that better 5-day mean temperature forecasts could be made by using as input to the objective method daily rather than mean prognoses of both temperature and height. As will be explained later, the method is therefore applied by using local temperature forecasts for day 1, designated by t_{FM}, and numerical (NMC) 36-hour height forecasts, valid at 0000 GMT on day 2, designated h_{36}. Thus, in current practice, T_4 is a function of t_{FM} and h_{36} rather than of T_0 and H_2 as originally derived.[4] Moreover, some evidence has recently been accumulated to show that the objective method may be useful in predicting the *daily* temperature for 3 days in advance, here designated t_3. On this basis, it is proposed that t_3 is a function of t_{FM} and h_{36} (fig. 2).

4. VERIFICATION OF 5-DAY MEAN FORECASTS

In order to document the preceding statements, we shall now present the results of some tests run on independent data under operating conditions during the past 3 years. Table 1 shows the percent of variance of 5-day mean temperature for the T_4 period explained by the prediction equations with various types of input. The forecasts were made at 39 cities for 12 weeks from October 2 to December 18, 1958, for a total of 468 cases.

The first line shows that only 9.3 percent of the variance was explained by use of 5-day mean temperature (T_0) and 5-day mean height (H_2) estimated in the manner described in the previous section. This value was increased to 21 percent (line 2) when NMC baroclinic 36-hour 700-mb. height forecasts (h_{36}) were substituted for the 5-day mean barotropic heights used in the first line. Although there are several reasons for this sizeable

[4] The anomalies of t_{FM} and h_{36} are routinely multiplied by 0.7 and 0.5 respectively, before insertion into the multiple regression equations. This multiplication has the effect of reducing the variability of the daily values about the normal to approximately the observed variability of the 5-day means

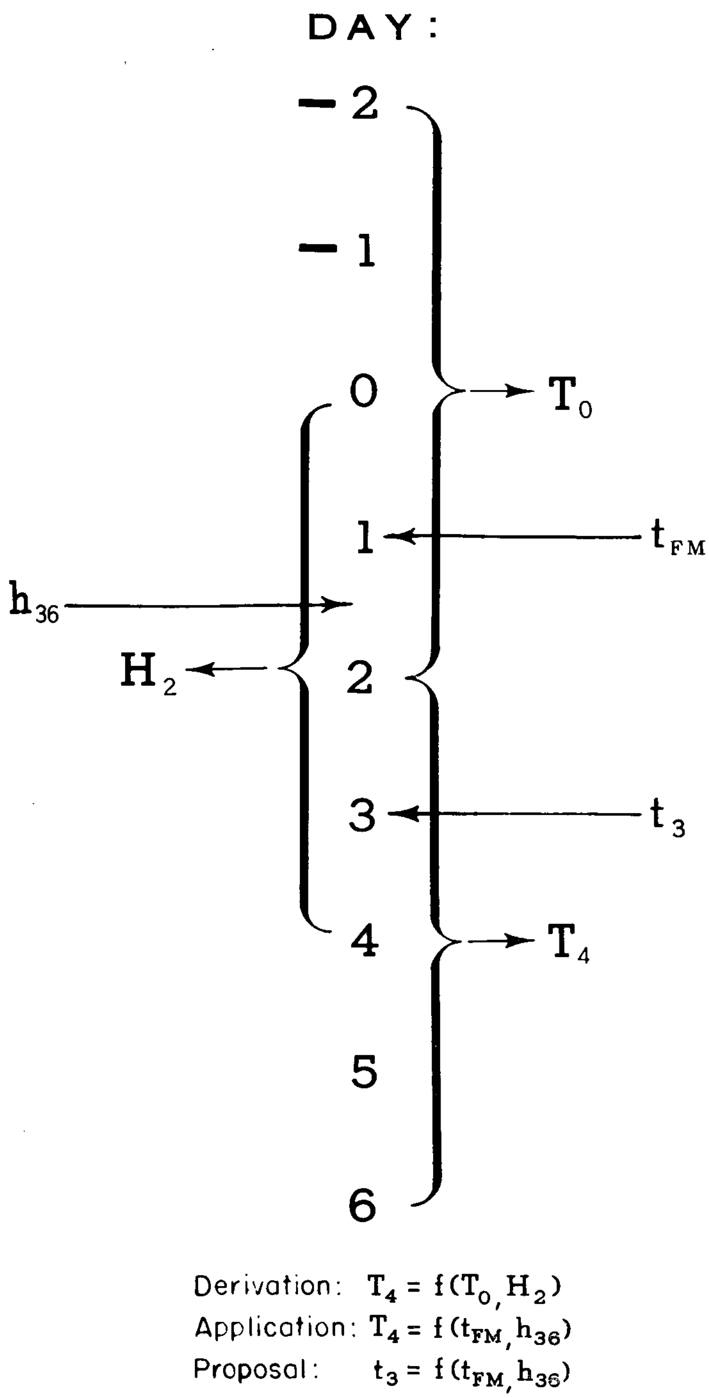

FIGURE 2.—Schematic calendar showing time periods involved in the objective forecasts. Various 5-day mean periods (capital letters) and daily periods (small letters) are depicted relative to forecast day (day 0). The valid time of prognostic quantities is shown by the arrows. Note that T_0 and T_4 contain day 2 in common.

improvement, the important thing is that no other prognostic heights, daily or mean, were able to yield better results. (For further details see [7].)

In view of this result it was decided to experiment with daily temperature as input in place of the estimated mean temperature T_0. Line 3 shows that use of the

TABLE 1.—*Percent of variance of 5-day mean temperature (T_4) explained by prediction equations during fall of 1958 (mean of 12 cases at 39 cities).*

Line	Derivation	Height input	Temperature input	Percent
1	Mean data	H_2	T_0	9.3
2	Mean data	h_{36}	T_0	21.0
3	Mean data	h_{36}	t_{-1}	17.0
4	Mean data	h_{36}	t_1	28.9
5	Mean data	h_{36}	t_{FM}	24.6
6	Daily data	h_{36}	t_{FM}	15.8
7	Daily data	h_{36}	700-mb. t_1	16.3

temperature observed on the day before forecast day (t_{-1}), in conjunction with h_{36}, explained only 17 percent of the temperature variance. This figure could be raised to 28.9 percent if temperatures observed the day after forecast day (t_1) were known perfectly in advance (line 4). The marked difference between lines 3 and 4 emphasizes the importance of later data. The best approximation to t_1 available on forecast day is t_{FM}, the local forecast for the next day, which produced an explained variance of 24.6 percent (line 5), a definite improvement over the 21 percent obtained by using T_0 (line 2). Part of the reason for this improvement lies in the fact that T_0 is centered one day earlier than t_{FM}.

It therefore seemed logical that better results might be obtained by rederiving the equations from the same type of input used in actual practice, namely, daily values of height and temperature for the next day. This was done by the screening program for the same 10 years of observed data used in the original derivation. Both surface and 700-mb. temperatures observed the day after forecast day were tried in conjunction with daily 700-mb. heights corresponding to h_{36}. Although the results on the developmental sample seemed promising with about 50 percent of the temperature variance explained in each case, a test of the new prediction equations on the 1958 fall sample explained only about 16 percent of the variance (lines 6 and 7). Apparently, raw daily data contain too much noise and instability to yield reliable prediction equations without some type of smoothing. Thus, under current operating conditions, it appears that equations derived from observed mean data and applied to daily prognostic data give the best mean forecasts.

In order to check the hypothesis that better results could be obtained by use of daily, rather than mean, temperature input, additional tests were run with data of the following year, with results shown in table 2. This verification is in terms of the five temperature classes [5], 100 grid points, and skill scores customarily used in extended forecasting. Three forecasts a week were made during the period September 15, 1959 to March 13, 1960, for a total of 77 5-day forecast periods. Table 2 compares the skill of the regression equations derived from mean

[5] In order to approximate the observed distribution of the five temperature classes the objective predictions were first multiplied by the reciprocal of the multiple correlation at each city [6].

TABLE 2.—*Comparative skill of objective 5-day mean temperature forecasts for T_4 period during fall of 1959 (37 cases from Sept. 15, 1959 to Dec. 8, 1959) and winter of 1959–60 (40 cases from Dec. 10, 1959 to Mar. 13, 1960).*

Height input	Temperature input	Skill scores		
		Fall	Winter	All
h_{36}	T_0	19.0	21.3	20.2
h_{36}	t_{FM}	20.5	22.7	21.7

data and applied to the same height input (h_{36}) but to two different types of temperature input, namely, the estimated 5-day mean (T_0) and the daily forecast (t_{FM}). In agreement with the findings shown in table 1, the verification shows a small but consistent superiority for the daily temperature input. As a result, the objective method is now run routinely with the daily quantities shown in the last line (h_{36} and t_{FM}) used as input to the prediction equations.

The most recent results are shown in table 3, where the verification is again in terms of 5 classes, 100 cities, and standard skill scores, but for the 8-month period from November 1960 through June 1961. The objective skill score of 17.5 (line 1) is superior to persistence of either the mean temperature T_0 (line 2) or the daily forecast t_{FM} (line 3). Line 4 shows that the official forecast advisories issued by the Extended Forecast Branch during this period were superior to the objective predictions. This is not surprising since the official forecaster makes use of the objective forecast plus numerous additional aids. However, the last line shows that the objective predictions were definitely better than the average of the official forecasts from 1952 to 1957, the latest period before numerical and objective tools became available [11].

5. SKILL ON EACH DAY OF THE PERIOD

We now turn to another phase of this study. Since use of daily input in equations derived from mean data gives skillful 5-day mean temperature forecasts, can equally good results be obtained by applying these equations to make daily forecasts? Of course, equations for this purpose could be derived directly, but perhaps considerable success might be achieved by applying the already existing equations. If we neglect the difference in spatial scale between daily and 5-day mean phenomena, the objective 5-day forecasts can be converted into daily ones merely

TABLE 3.—*Verification of various 5-day mean temperature forecasts for T_4 period in terms of 5 classes at 100 cities in the United States (102 cases, November 1960–June 1961)*

Line	Method	Skill score
1	Objective using daily input (h_{36} and t_{FM})	17.5
2	Persistence of estimated mean temperature (T_0)	11.6
3	Persistence of daily forecast (t_{FM})	12.7
4	Official—Extended Forecast Branch	18.5
5	Official, 1952–1957	13.9

by increasing their numerical magnitude to compensate for the increased variability of daily compared to 5-day mean temperatures. For this purpose, it is necessary to multiply the predictions by the ratio of the standard deviation of daily temperature to the standard deviation of 5-day mean temperature. After considerable experimentation, it was found that best results could be obtained by using a value of 1.4 for this ratio. This figure can be derived theoretically from equations given by Brooks [1] and Jenkinson [5] by making the reasonable assumption that the persistence of daily temperature dies away exponentially with a 1-day lag autocorrelation coefficient of 0.6 [13]. A more accurate procedure would have been to obtain separate conversion factors for each city and each month on the basis of observed standard deviations, but for the purposes of this pilot project a ratio of 1.4 was used for all forecasts.[6]

Figure 3 is for the same 100 points, 5 temperature classes, and 37 cases during the fall of 1959 used in table 2, but this verification was obtained from temperatures observed on each individual day,[7] rather than from the 5-day mean. The abscissa gives the number of days after forecast day (0) for which the forecast was verified, where days 2 to 6 constitute the customary 5-day forecast period. The ordinate shows the percent of the contiguous United States which was predicted in exactly the correct temperature class. The horizontal dashed line gives the amount that would be expected correct by chance, 22 percent. This is slightly lower than the score that would be expected by always forecasting the climatological normal, 25 percent.

The open circles represent the score of the objective predictions verified as daily forecasts. This score reaches a maximum of almost 40 somewhere between the 2d and 3d days and then drops off rapidly, although remaining above chance even on the 6th or final day of the period. If the objectives were perfect 5-day mean temperature forecasts, they would still fall short of 100 percent accuracy as daily forecasts. This is indicated by the dashed curve in figure 3, which was obtained from 5-day mean temperatures actually observed during the fall of 1959. Although this curve reaches a peak as expected on the 4th or middle day of the 5-day period, even on this day it scores only about 56 percent correct. The differences between the curve for the objective and that for the perfect mean indicate first, that the objective method can still stand a lot of improvement, and second, that the objective forecasts tend to be too slow; i.e., to be more accurate at the beginning than at the end of the 5-day forecast period.

The remaining two curves are persistence controls.

[6] The same ratio has been applied to 5-day mean temperature class limits to obtain approximate daily class limits by means of which any observed or prognostic chart of daily temperature anomaly can be analyzed in terms of the 5 standard classes. These daily class limits were used to analyze the observed daily temperatures in figure 3 as well as t_{FM} in table 3 (line 3).

[7] The daily temperature is computed by taking the mean of the maximum and minimum.

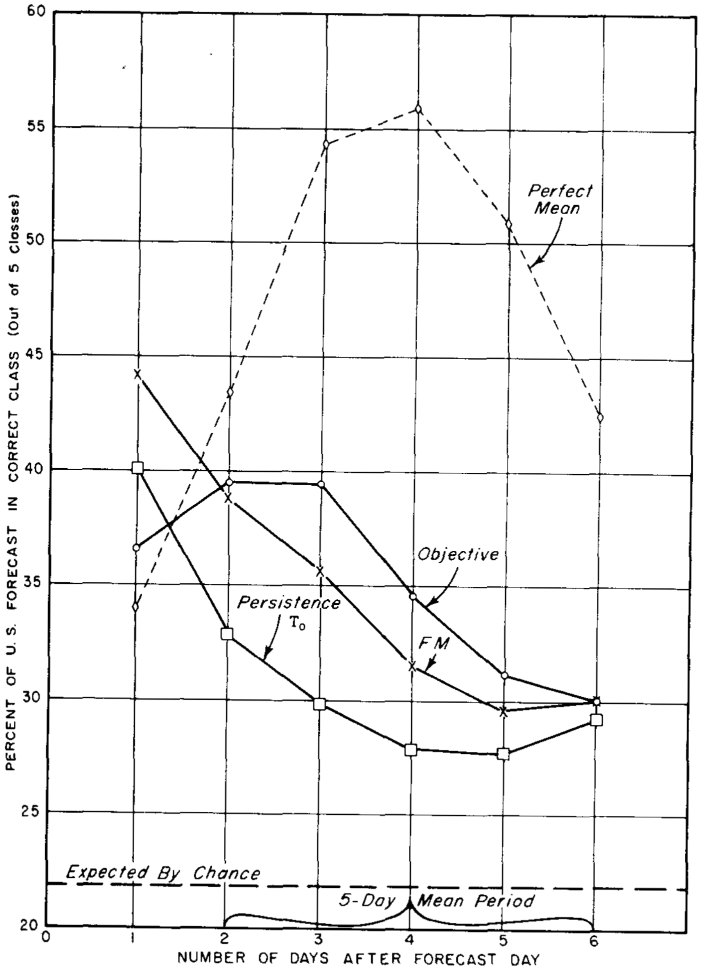

FIGURE 3.—Percent correct for various forecasts verified in terms of temperatures observed on each individual day of the period (analyzed by means of daily class limits) for 37 cases from September 15 to December 8, 1959. The open circles were obtained from the objective forecasts, the open squares from the 5-day mean centered on forecast day (T_0), the x's from persistence of the local forecasts for day 2 (FM), and the open diamonds from the 5-day mean temperatures actually observed.

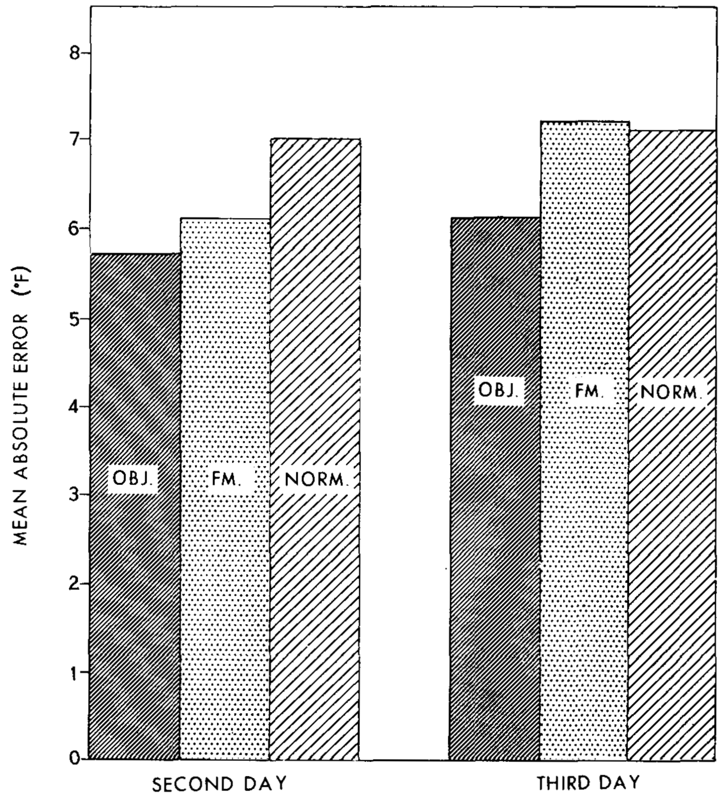

FIGURE 4.—Mean absolute error in forecasts of daily temperature 2 and 3 days in advance by objective method (OBJ), local forecast (FM), and the climatological normal (NORM). All results are averaged for 39 cities and 55 forecasts from October 27, 1960 to March 2, 1961.

The line of open squares was obtained from the estimated 5-day mean temperature centered on forecast day (T_0) and is similar to what would be obtained by use of the latest daily observed temperature. A later and therefore more skillful measure of persistence is given by the line of x's, obtained by using the local forecasts or FM's for day 2.[8] Theoretically this curve should peak on the second day, but it actually scores highest on day 1, thereby indicating that the FM forecasts (like the objectives) tend to be too slow. The most important feature of figure 3 is the fact that the objective forecasts scored higher than either T_0 or t_{FM} on each day of the 5-day mean period (days 2 to 6), with maximum difference on day 3.

[8] Until this point, the FM forecasts for the first day, or t_{FM} have been used in this paper. From now on, the FM forecasts valid on the second day will be used. When analyzed in terms of daily class limits and verified as persistence forecasts for the 5-day mean period, the latter scored about one point higher than the former during the 15-month period from April 1960 through June 1961 (skill scores of 12.8 and 11.6, respectively).

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6. FORECASTS FOR 2 AND 3 DAYS IN ADVANCE

In order to test further the ability of the objective method to predict daily temperatures, all objective forecasts made during the cool season of 1960–61 were converted to daily forecasts (by multiplying by 1.4) and then compared to the mean daily temperature actually observed 2 and 3 days later. Figure 4 gives the average error, taken without regard to sign, at 39 cities scattered over the United States on 55 days from October 27, 1960, to March 2, 1961, for 2- and 3-day temperature predictions.

The FM's valid on day 2 had a smaller average error than climatology on that day, but persistence of the 2d day FM's through the 3d day would lead to slightly larger errors than forecasts of normal for that day. A somewhat similar conclusion was reached by Gleiter [4] in an earlier investigation of the accuracy of the FM forecasts. The objective predictions had smaller absolute errors than the FM's or the normal on both the 2d and 3d days, but the margin of superiority over the FM's was very small on day 2, in general agreement with the results shown in figure 3.

These results are for the entire United States without geographical differentiation. During the winter of 1960–

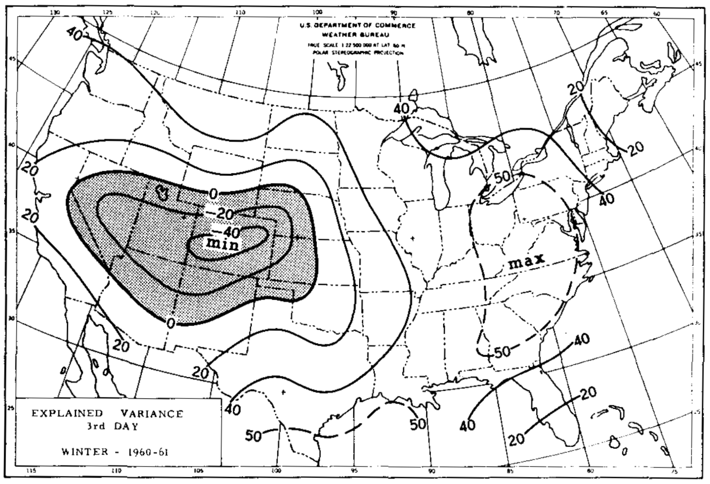

FIGURE 5.—Percent of variance of daily surface temperature explained by the objective method used as a 3-day forecast. Data based on 39 forecasts at each of 30 cities during December 1960, January 1961, and February 1961. Area in which forecasts were worse than climatology is shaded.

61 the objective forecasts were generally more accurate in the eastern than in the western half of the country, probably because of sparsity of data in the Pacific. This is well illustrated by figure 5 which gives the percent of temperature variance 3 days in advance explained by the objective predictions in different parts of the country on 39 days from December 1, 1960, to February 28, 1961. Except for an area of negative values (shaded) in the southern Rocky Mountain States, the objective method generally showed positive skill; i.e., it explained more of the temperature variance than did the normal for the 3d day. The average explained variance over the entire country was 29 percent. If these geographical differences hold in future years, selective use of the objective method could lead to a better verification.

An interesting feature of figure 4 is the fact that the objective forecasts had a slightly smaller error on the 2d day than they did on the 3d day. The feasibility of utilizing the objective method to prepare 48-hour temperature forecasts was therefore investigated. Until now all values of h_{36} used as input for the prediction equations were prepared from 1200 GMT upper level data. In order to obtain a fair comparison with the FM forecasts (which are prepared around 0900 GMT), it was necessary to use values of h_{36} based on observations made 12 hours earlier (at 0000 GMT). This was done for 29 days of the past winter with results summarized in table 4. The objective forecasts (line 1) are now no longer superior to the FM's (line 2), although still considerably better than climatology (line 3).

The last three lines of the table give the results of some experiments designed to speed up issuance of the objective

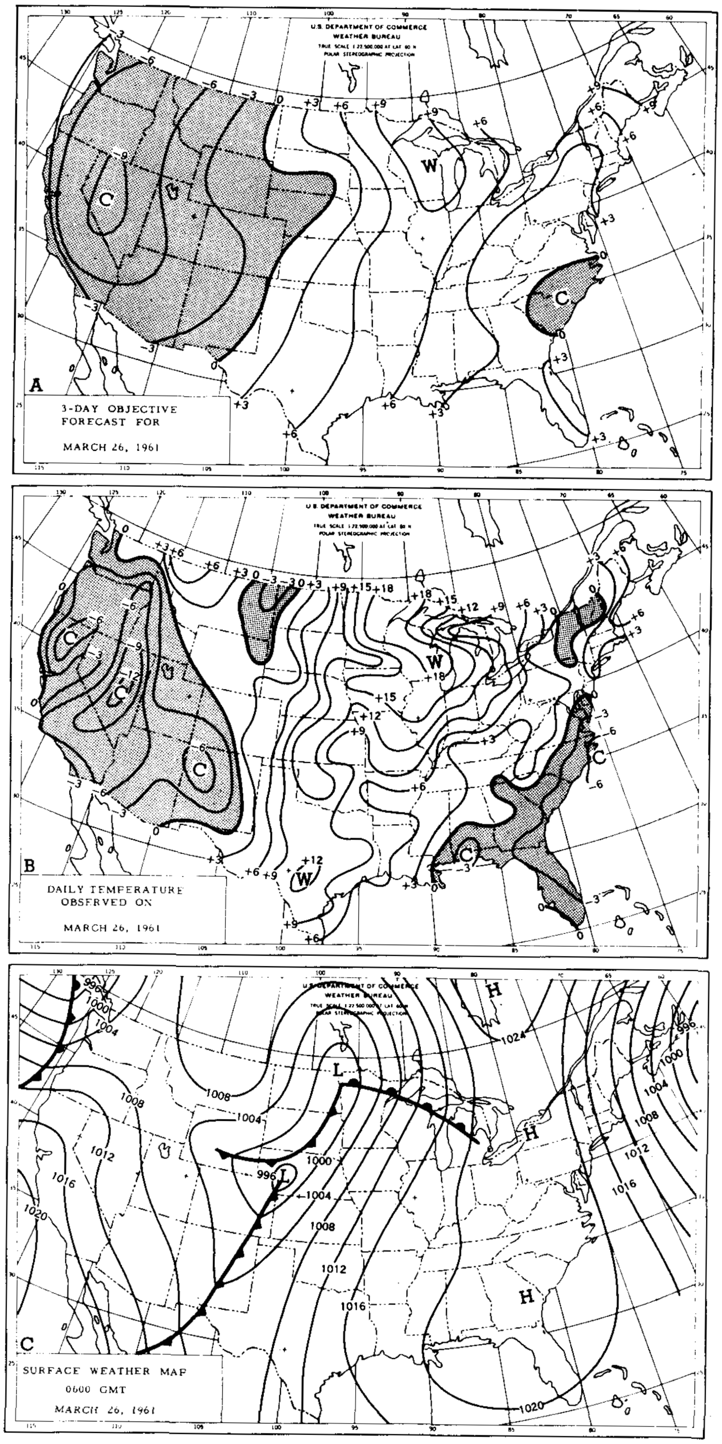

FIGURE 6.—(A) Objective 3-day forecast of daily surface temperature anomalies for March 26, 1961. (B) Observed surface temperature anomalies, March 26, 1961. (A) and (B) are analyzed for every 3°F. with below normal temperatures shaded. Centers of cool and warm air (relative to normal) are labeled C and W respectively. (C) Surface weather map observed at 0600 GMT, March 26, 1961, with sea level isobars labeled in millibars and conventional symbols for fronts, Highs, and Lows.

TABLE 4.—*Mean absolute error in forecasts of daily temperature (°F.) for 2 days in advance (t_2) Jan. 10 to Mar. 21, 1961. (Mean of 29 forecasts at 30 cities.) All objective forecasts based on 0000 GMT upper air data.*

Line	Method	Error
1	Objectives using h_{36} and t_{FM}	6.6
2	FM for day 2	6.4
3	Climatological normal	7.6
4	Objectives using h_{36} and t_{-1}	6.9
5	Objectives using h_0 and t_{FM}	6.9
6	Objectives using h_0 and t_{-1}	7.1

forecasts by changing heights and temperatures used as input in the prediction equations from prognostic values (h_{36} and t_{FM}) to latest observed values (h_0 and t_{-1}). Comparison with line 1 shows that such a procedure would lead to deterioration of the forecasts, which should be based on the best short-range predictions available in order to achieve maximum skill. In view of these results, it would not appear to be operationally feasible to prepare 48-hour temperature forecasts by the objective method at the present time.

However, figures 3 and 4 show that it would be distinctly advantageous to prepare objective temperature forecasts for the 3d day, a time for which no forecast is currently issued to the public. These forecasts can occasionally supply useful clues about the orientation of sea level isobars, the nature of air masses, or the location of frontal zones. A good example is illustrated in figure 6. The objective prediction made March 23, 1961 (fig. 6A) called for unseasonably cold temperatures in the western third of the country, warm weather in the Midwest, and near normal temperatures in the East. The daily temperatures observed on March 26 (fig. 6B) show that this forecast verified quite well 3 days later, although not with nearly enough detail or intensity. The synoptic map for 0600 GMT March 26 (fig. 6C) contained a sharp surface front through the center of the Nation, very close to the line of normal temperature (zero line) in the objective prediction.

7. CONCLUSION

It has been shown that under current operating conditions better objective forecasts of 5-day mean temperature can be obtained from short-range prognoses of both 700-mb. height and surface temperature than from estimates of the 5-day mean values of these elements from which the prediction equations were originally derived. Since re-derivation from unsmoothed daily data yielded poorer results, it may be concluded that equations derived from observed mean data and applied to daily prognostic data give the best mean forecast in the framework of this objective system. Although the resulting objective predictions of 5-day mean temperature tend to be too slow, nevertheless they are superior to the official forecasts made by more subjective methods used in earlier years.

It has also been shown that 3-day temperature forecasts made by the objective method have skill beyond chance, climatology, persistence, or short-period predictions. In part as a result of this finding, facsimile transmission of 3-day temperature forecasts, along with a 72-hour prognostic surface map, was initiated by the Extended Forecast Branch of the U.S. Weather Bureau on September 18, 1961. In the routine preparation of these forecasts, the objective temperature method is employed alongside numerous other tools.

ACKNOWLEDGMENTS

The generous assistance of the following employees of the U.S. Weather Bureau in various phases of the data processing is gratefully acknowledged: Mrs. Mary Abernathy, Mr. George Casely, Mr. Michael Gaidurgis, and Mr. Donovan Truesdell.

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